PRECISION MEASUREMENT OF THE HIGGS BOSON MASS AND SEARCH FOR DILEPTON MASS RESONANCES IN $H \rightarrow 4\ell$ DECAYS USING THE CMS DETECTOR AT THE LHC

By

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This work is dedicated to the living and loving memory of Jacob Myhre.

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By

Jake Rosenzweig

August 2022

Chair: Andrey Korytov
Co-Chair: Guenakh Mitselmakher
Major: Physics

The mass of the Higgs boson is measured in the $\mathrm{H} \to \mathrm{ZZ}^* \to 4\ell$ ($\ell = \mathrm{e}, \mu$) decay channel and is found to be $m_{\mathrm{H}} = 125.38 \pm 0.11\,\mathrm{GeV}$; the world's most precise measurement to date. The data for the measurement were produced from proton-proton (pp) collisions at the Large Hadron Collider with a center-of-mass energy of 13 TeV during Run 2 (2016–2018), corresponding to an integrated luminosity of $137.1\,\mathrm{fb}^{-1}$, and were collected by the Compact Muon Solenoid experiment. This measurement uses an improved analysis technique in which the final state muon tracks are constrainted to originate from the primary pp vertex. Using data sets from the same run, a search for low-mass dilepton resonances in Higgs boson decays to the 4ℓ final state is also conducted. No significant deviation from the Standard Model prediction is observed.

CHAPTER 1
INTRODUCTION

The Universe, while overwhelmingly vast, is built from a remarkably few kinds of elementary (i.e., indivisible) particles. As shown in Fig. 1-1, any elementary particle can be classified into 1 of these 3 categories: matter particles (*fermions*), force-carrying particles (*gauge bosons*), and Higgs bosons. There are 12 kinds of fermions which can be split evenly into 2 groups, depending on with which forces they interact: those that interact via the electromagnetic (EM) force and the weak nuclear force are classified as *leptons*, of which there are 6 kinds (*"flavors"*), whereas those that interact via the EM, weak, *and* strong nuclear forces are classified as *quarks*, of which there are also 6 flavors. There are 4 kinds of gauge bosons, each of which is a force carrier for a specific force (the gluon is said to *mediate* the strong force, the photon mediates the EM force, while both the $W^{\pm}$ and Z bosons mediate the weak force). Thus, all the diversity and manifestations of reality come from only 17 kinds of "building blocks". It is the mission of particle physicists to understand the underlying mathematical structure that describes Nature in as accurate—and hopefully *concise*—a theory as possible. The best theory that stands today is called the Standard Model (SM) of particle physics.

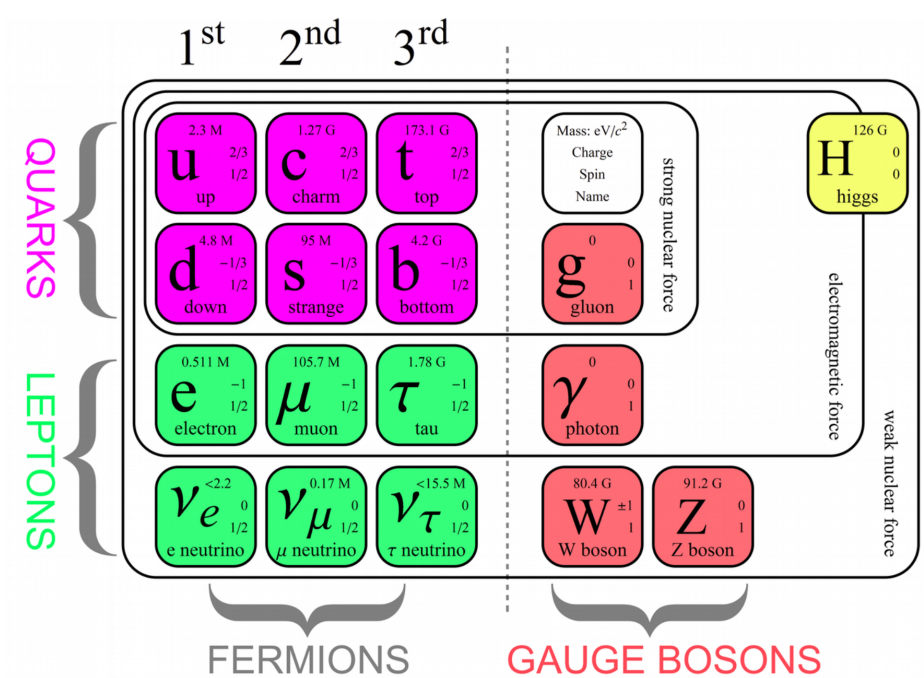

Figure 1-1. The elementary particles described by the SM.

The SM has bore witness to many triumphs over its approximately 70-year development: it predicted the existence of quarks which were experimentally confirmed in the mid-1970s; it predicted the existence of the tau neutrino which was experimentally confirmed in 2000; its most groundbreaking prediction was experimentally confirmed on July 4, 2012—almost exactly 10 years ago from the date of this dissertation writing—when the ATLAS and CMS collaborations announced the discovery of the Higgs boson [1, 2, 3].

Quantum Field Theory is the mathematical and conceptual backbone of the SM. Within its framework, all particles are *excitations* of their corresponding field so, e.g., *every* electron in the Universe is thought to be an excitation of the single electron field that permeates all of spacetime. The existence of the Higgs boson (H) suggests that its corresponding field exists—the *Higgs field*—and that H is the quantum excitation of that field. This all-pervasive Higgs field and its corresponding boson are generated mathematically via the Brout-Englert-Higgs (BEH) mechanism. Most SM particles—except for neutrinos, photons, and gluons—"acquire" their mass by interacting with the Higgs field. This is also how the Higgs boson itself acquires its mass (m_{H}): by interacting with its own field!

The masses of SM particles *depend* on the value of m_{H} . . . *so what is its value?* Unfortunately, m_{H} is a free parameter of the SM, so theory is unable to provide a value for m_{H} based solely on other fundamental constants. Instead, the value of m_{H} must be measured by experiment. TODO:CITE LOTS OF PEEPS [**?**] Although the value of m_{H} was measured back in 2012, it is always important to improve the measurement by lowering the uncertainties on (i.e., increasing the precision on) the mass value. A more precise value of m_{H} improves theoretical limits on the masses of most of the other elementary particles and may very well determine the ultimate stability of our universe, as shown in Fig. 1-2.

Plus, as mentioned previously, Furthermore, the value of m_{H}.

The production of a Higgs boson is only feasible at conditions close to those thought to exist at the beginning of the Universe. This grand achievement is accomplished frequently by the Large Hadron Collider (LHC), located on the border of France and Switzerland. It is the largest and

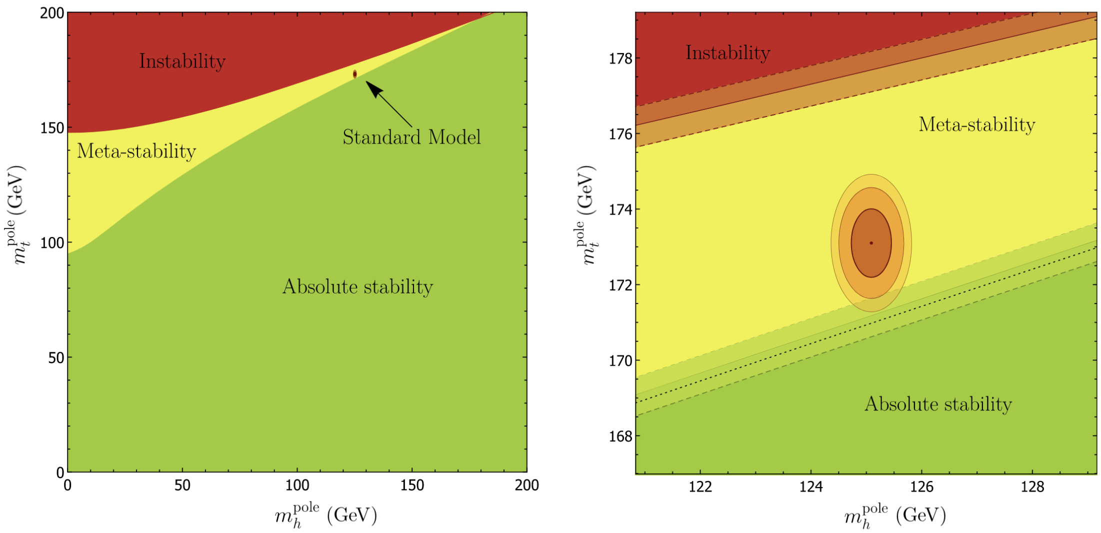

Figure 1-2. (Left) Theoretical stability regions of our universe based on the pole masses of the top quark $\left(m_t^{\text{pole}}\right)$ and Higgs boson $\left(m_h^{\text{pole}}\right)$. (Right) A closeup of the SM region of the left plot. The contours represent the 68%, 95%, and 99% confidence levels based on the experimental uncertainties of m_t^{pole} and m_h^{pole}. Plots taken from [4] and units added to all axes.

most powerful proton-proton (pp) collider ever made. The LHC accelerates protons to near-light speeds and produces pp collisions with center-of-mass energies as high as 13 TeV, Old and newly produced particles spew out of the collisions points and are analyzed by detectors like the aforementioned ATLAS and CMS experiments. These enormous particle detectors have thousands of scientists performing dozens of analyses to look for hints of beyond Standard Model (BSM) physics, extra dimensions, miniature black holes, and more. This dissertation utilizes data collected by the CMS experiment during the LHC Run 2 (2016–2018) to perform a precision measurement of the Higgs boson mass (m_{H}).

The measurement of m_{H} presented in this dissertation utilizes the following improvements compared to previous measurements:

- Utilizing nearly four times as much collected data from Run 2 $\left(\mathcal{L}_{\text{int}} = 137.1\,\text{fb}^{-1}\right)$ vs. the data used for the 2016 measurement $\left(\mathcal{L}_{\text{int}} = 35.9\,\text{fb}^{-1}\right)$.
- Four final-state categories are used: 4μ, 4e, $2\text{e}2\mu$, $2\mu2\text{e}$. In previous measurements, the last two final states (the mixed-flavor states) were combined, when truly they have different

kinematical properties (depending on into which lepton pair the Z_1 decayed): different peak widths (instrumental resolutions), different signal efficiencies, and different relative levels of reducible background.

- Ultra-Legacy (UL) reconstruction is used for muon, electron, photon, and jet tracks. This signficantly improves electron momenta and improves the other particle momenta, though to a lesser degree.

- The measurements of muon p_{T} are improved by constraining the muon tracks to originate from the interaction vertex (also called a *vertex constraint*).

- When extracting the value of m_{H} in past measurements, a 3D pdf $\left(m_{4\ell}, \sigma_{m_{4\ell}}, \mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}}\right)$ was built into a factorized form $f\left(m_{4\ell}, \sigma_{m_{4\ell}} \,\middle|\, m_{\mathrm{H}}\right) \cdot g\left(\mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}} \,\middle|\, m_{4\ell}\right)$, which was later found to contain an existing correlation between $\sigma_{m_{4\ell}}$ and $\mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}}$. To account for this correlation, now the events are split into 9 categories based on the per-event *relative* mass uncertainty $\left(\frac{\sigma_{m_{4\ell}}}{m_{4\ell}}\right)$ and, for each, a 2D pdf $\left(m_{4\ell}, \mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}} \,\middle|\, m_{\mathrm{H}}\right)$ is built.

- The systematic uncertainties on electron and muon momentum scales $\left(p_{\mathrm{T}}^{\mathrm{e},\mu}\right)$ are reduced, thanks to a more detailed analysis on the uncertainties. This has the additional effect of significantly reducing the uncertainty on the per-event four-lepton mass resolution.

The following chapters of this dissertation begin with a thorough description of the CMS Experiment and its composite subdetectors in Chapter **??**. Next, the details of the precision measurement of the Higgs boson mass using the LHC Run 2 data is discussed in Chapter **??**. Finally, the results of the Higgs boson mass measurement analysis is summarized in Chapter 2.

CHAPTER 2
CONCLUSION

We measured it, boys.

REFERENCES

[1] S. Chatrchyan et al., *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Physics Letters B* **716** (2012) 30.

[2] S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan, W. Adam, T. Bergauer et al., *Observation of a new boson with mass near 125 GeV in pp collisions at* $\sqrt{s} = 7$ *and* $8\,TeV$, *Journal of High Energy Physics* **2013** (2013) 81.

[3] G. Aad, T. Abajyan, B. Abbott, J. Abdallah, S. Abdel Khalek, A.A. Abdelalim et al., *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Physics Letters B* **716** (2012) 1.

[4] A. Andreassen, W. Frost and M.D. Schwartz, *Scale-invariant instantons and the complete lifetime of the standard model*, *Phys. Rev. D* **97** (2018) 056006.

BIOGRAPHICAL SKETCH

This is the “biographical sketch" tex file, which should have been set in the main file using the command `\setBiographicalFile{Drive:/file/location/biographyFile}`.

Keep in mind this should be written in **third person** and should assume you have already completed your degree that you are writing this thesis or dissertation for. For example:

Jason is a person that wrote some code, did some research, and eventually got a PhD in mathematics for some stuff. He had to actually write a real biographical sketch because he had forgotten to do it until final submission.